CSE 167:
Introduction to Computer Graphics
Lecture #9: Texture Mapping

Jürgen P. Schulze, Ph.D.
University of California, San Diego
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Announcements

- Sunday, November 1st at 11:59pm:
  - Homework Project 1 late deadline
  - 25% penalty on score
- Sunday, November 8th at 11:59pm:
  - Homework Project 2 due

Lecture Overview

- Texture Mapping
  - Overview
  - Wrapping
  - Texture coordinates

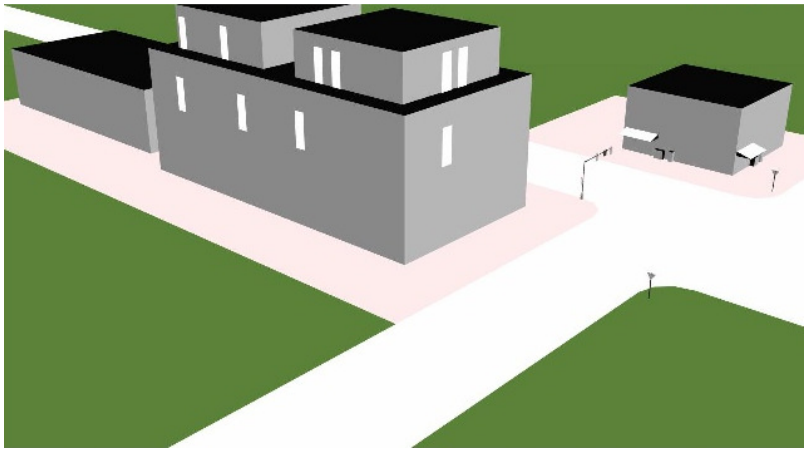
Large Triangles

Pros:

- Often sufficient for simple geometry
- Fast to render

Cons:

- Per vertex colors look boring and computer-generated

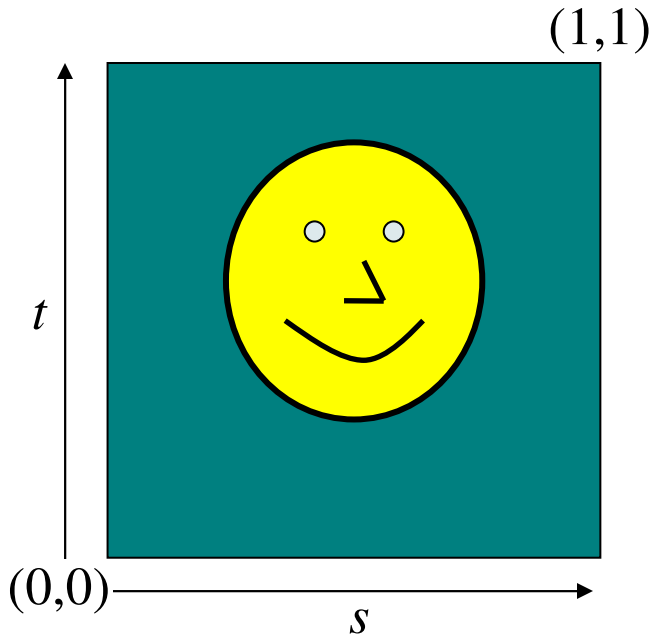


Texture Mapping

- Map textures (images) onto surface polygons
- Same triangle count, much more realistic appearance

Texture Mapping

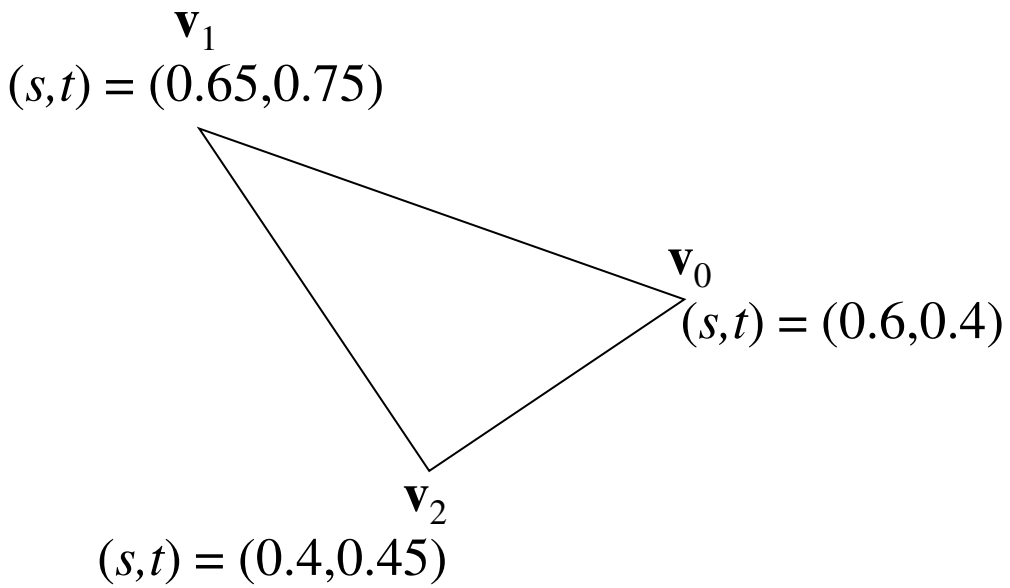
- Goal: map locations in texture to locations on 3D geometry
- Texture coordinate space
  - Texture pixels (texels) have texture coordinates (s,t)
- Convention
  - Bottom left corner of texture is at $(s,t) = (0,0)$
  - Top right corner is at $(s,t) = (1,1)$



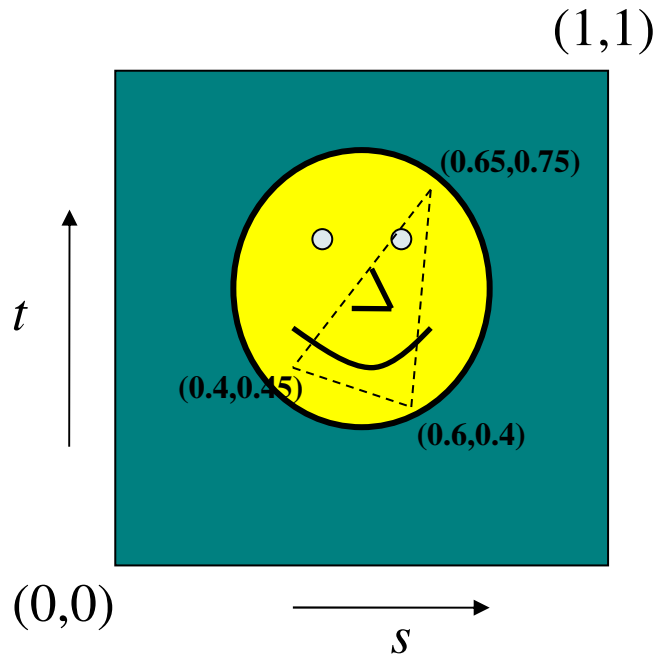
Texture coordinates

Texture Mapping

- Store 2D texture coordinates s,t with each triangle vertex



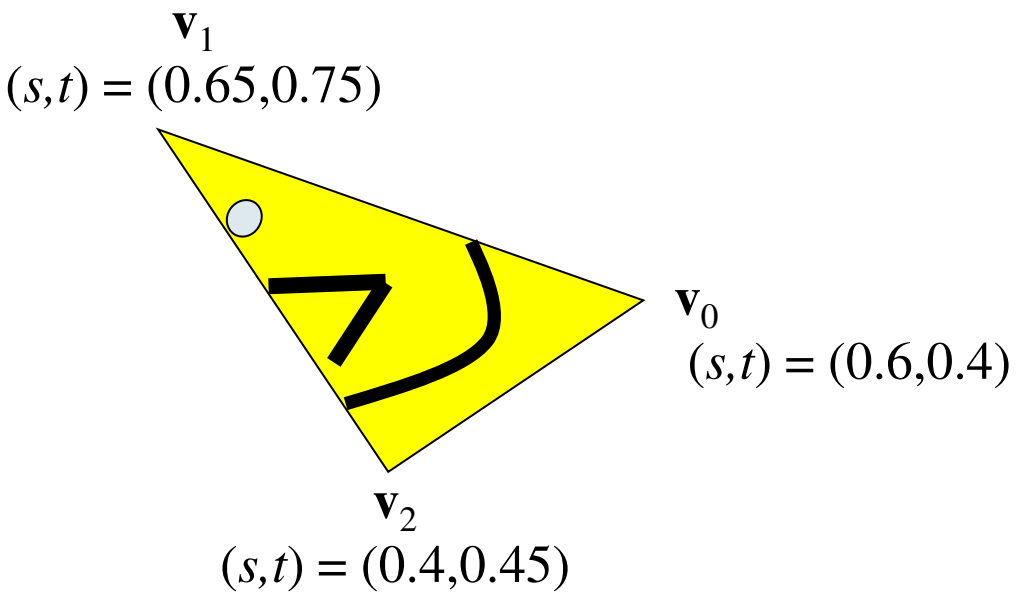
Triangle in any space before projection



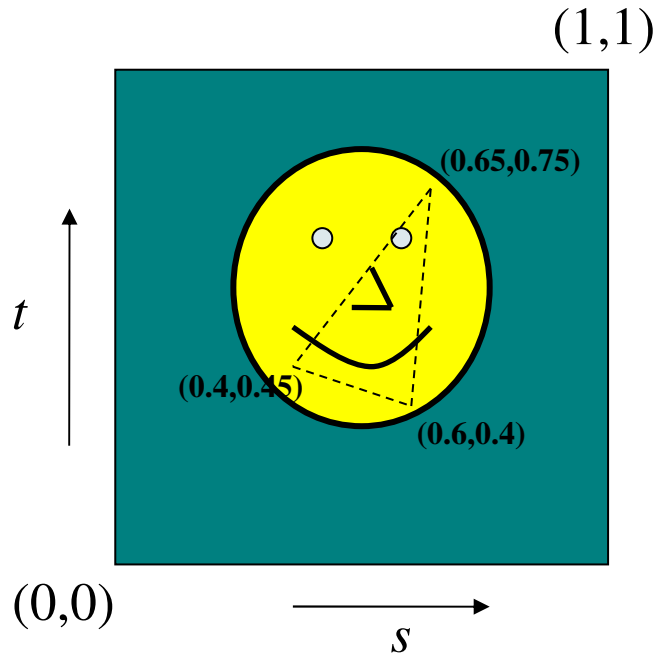
Texture coordinates

Texture Mapping

- Each point on triangle gets color from its corresponding point in texture

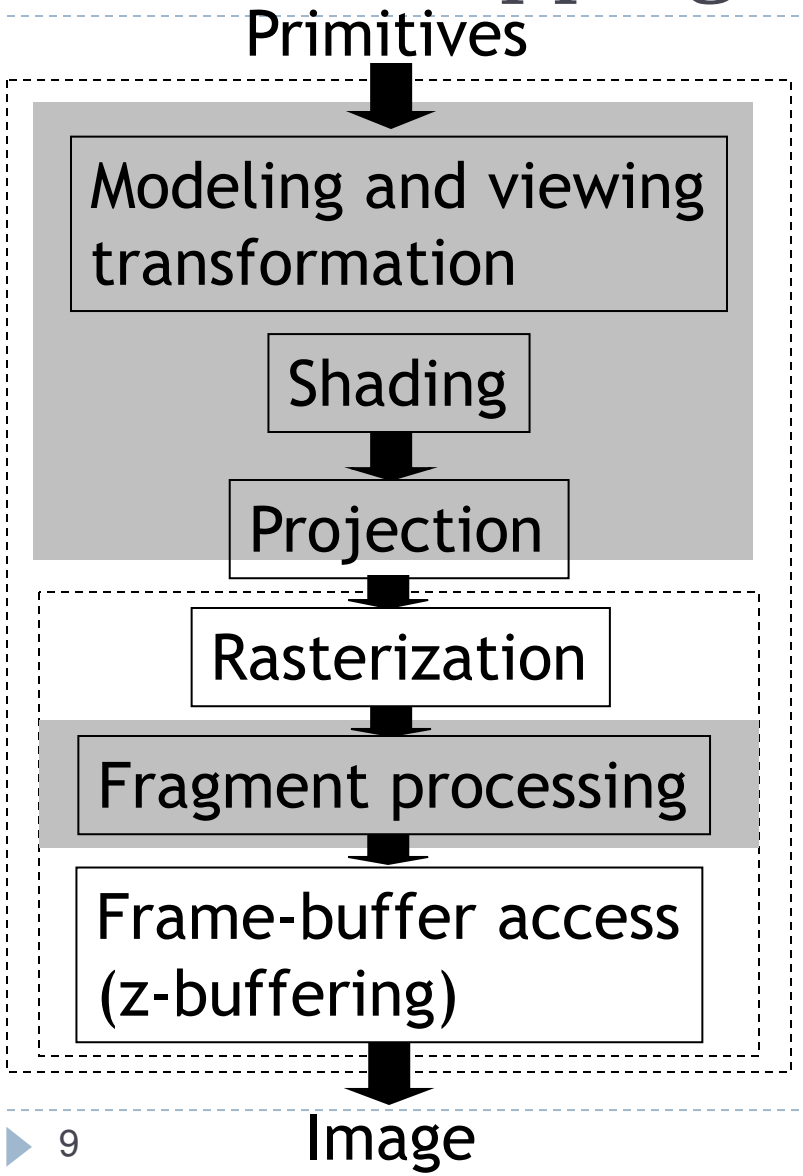


Triangle in any space before projection



Texture coordinates

Texture Mapping

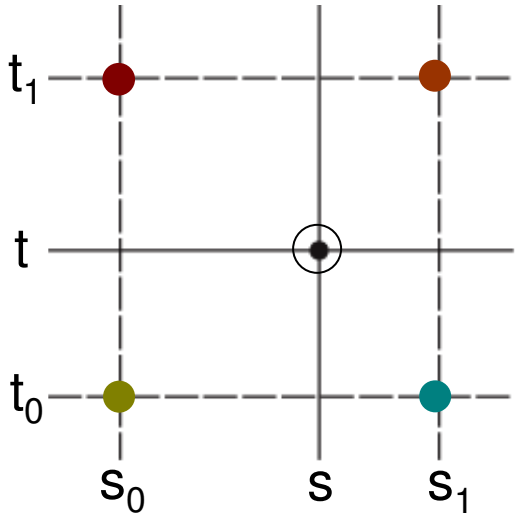


Includes texture mapping

Texture Look-Up

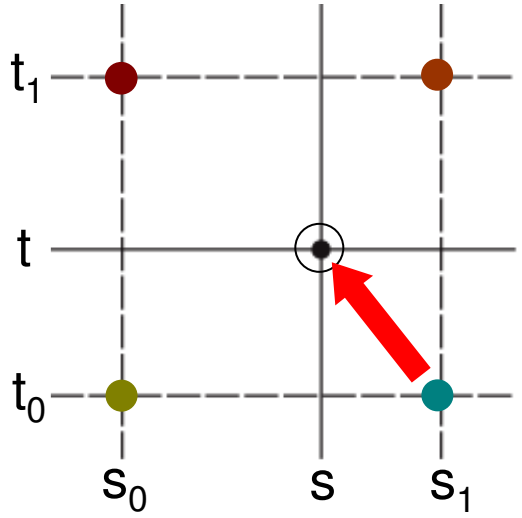
- Given interpolated texture coordinates (s, t) at current pixel
- Closest four texels in texture space are at

  (s_0,t_0), (s_1,t_0), (s_0,t_1), (s_1,t_1)
- How to compute pixel color?



Nearest-Neighbor Interpolation

- Use color of closest texel



- Simple, but low quality and aliasing

Bilinear Interpolation

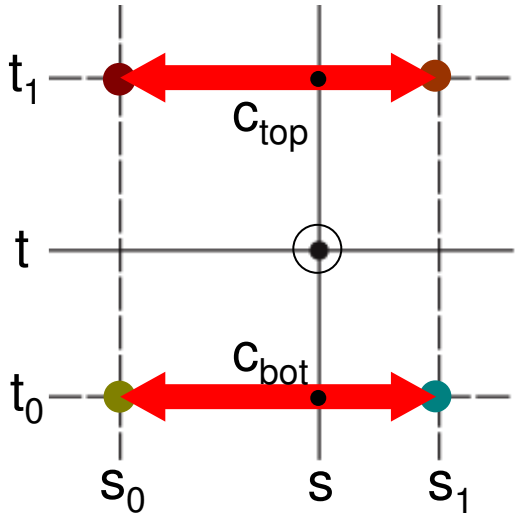
1. Linear interpolation horizontally:

   Ratio in s direction r_s:

$$r_s = \frac{s - s_0}{s_1 - s_0}$$

$c_{top} = tex(s_0,t_1)\ (1-r_s) + tex(s_1,t_1)\ r_s$

$c_{bot} = tex(s_0, t_0)\ (1-r_s) + tex(s_1,t_0)\ r_s$



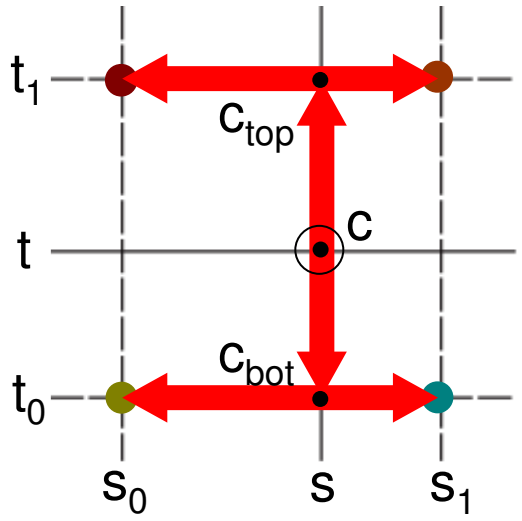
Bilinear Interpolation

2. Linear interpolation vertically

Ratio in t direction r_t:

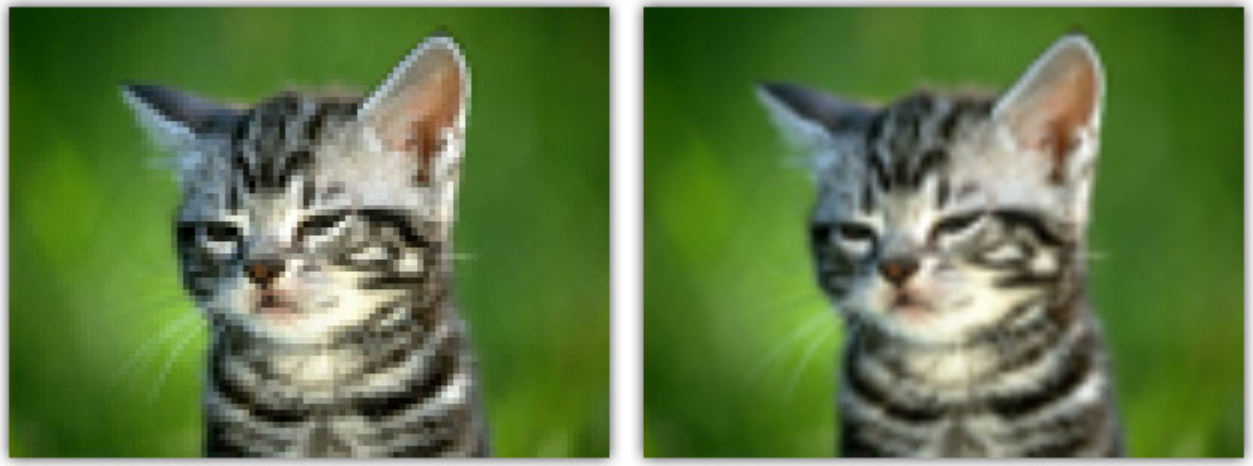
$$r_t = \frac{t - t_0}{t_1 - t_0}$$

$c = c_{bot} (1-r_t) + c_{top} r_t$



Texture Filtering in OpenGL

- GL_NEAREST: Nearest-Neighbor interpolation
- GL_LINEAR: Bilinear interpolation
- Example:
  - glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR);
  - glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR);



Source: https://open.gl/textures

Lecture Overview

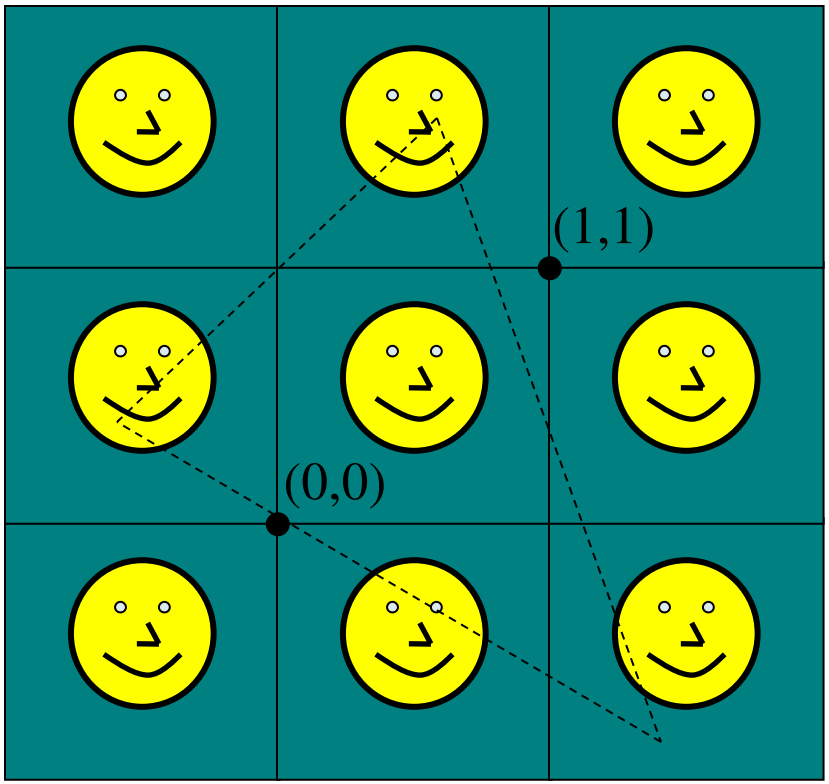
- Texture Mapping
  - Overview
  - Wrapping
  - Texture coordinates

Wrap Modes

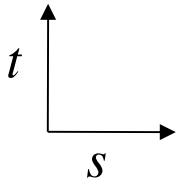
- Texture image extends from $[0,0]$ to $[1,1]$ in texture space
  - What if (s,t) texture coordinates are beyond that range?
- → Texture wrap modes

Repeat

- Repeat the texture
  - Creates discontinuities at edges
    - unless texture is designed to line up



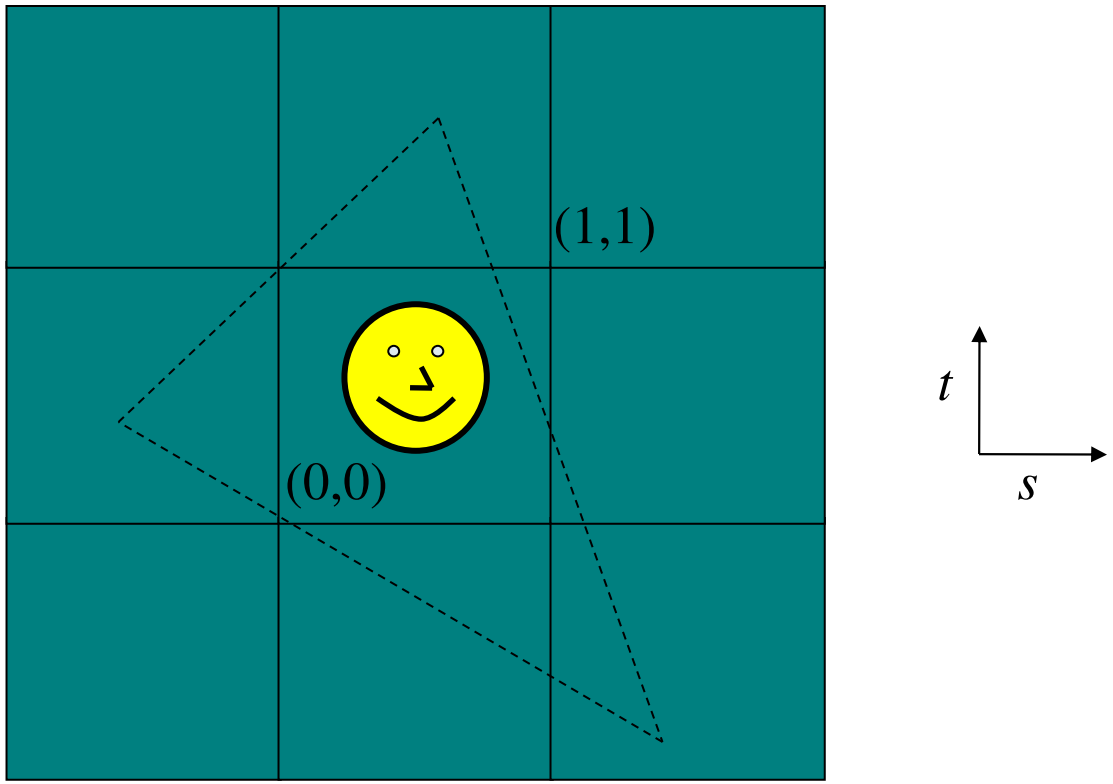
Texture Space



Seamless brick wall texture
(by Christopher Revoir)

Clamp

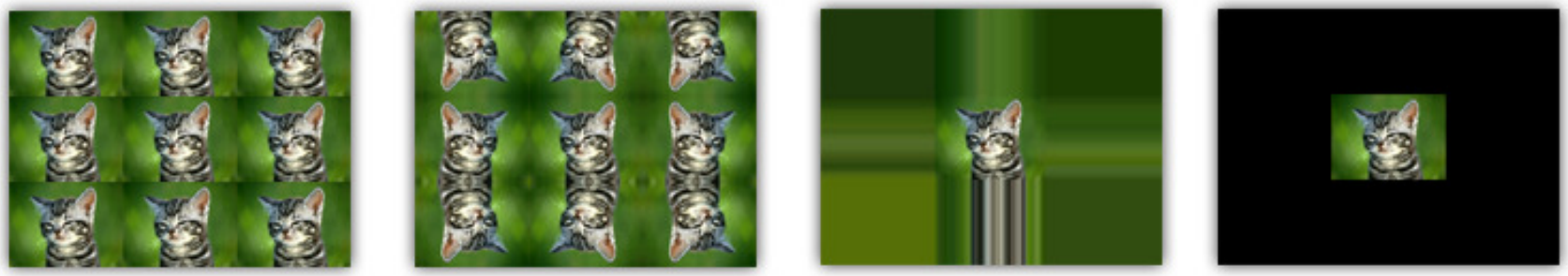
- Use edge value everywhere outside data range [0..1]
- Or use specified border color outside of range [0..1]



Texture Space

Wrap Modes in OpenGL

- Default:
  - glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT);
  - glTexParameterf(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT);
- Options for wrap mode:
  - GL_REPEAT
  - GL_MIRRORED_REPEAT
  - GL_CLAMP_TO_EDGE: repeats last pixel in the texture
  - GL_CLAMP_TO_BORDER: requires border color to be set



Source: https://open.gl/textures

OpenGL Example: Loading a Texture

```
// Loads image as texture, returns ID of texture
GLuint loadTexture(Image* image)
{
  GLuint textureId;

  glGenTextures(1, &textureId); // Get unique ID for texture
  glBindTexture(GL_TEXTURE_2D, textureId); // Tell OpenGL which texture to edit
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR); // set bi-linear interpolation
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR); // for both filtering modes
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE); // set texture edge mode
  glTexParameteri(GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE);

  Image* image = loadJPG("photo.jpg");  // load image from disk; uses third party Image library

  // Depending on the image library, the texture image may have to be flipped vertically

  // Load image into OpenGL texture in GPU memory:
  glTexImage2D(GL_TEXTURE_2D,      // Always GL_TEXTURE_2D for image textures
     0,                            // 0 for now
     GL_RGB,                       // Format OpenGL uses for image without alpha channel
     image->width, image->height,  // Width and height
     0,                            // The border of the image
     GL_RGB,           // GL_RGB, because pixels are stored in RGB format
     GL_UNSIGNED_BYTE, // GL_UNSIGNED_BYTE, because pixels are stored as unsigned numbers
     image->pixels);               // The actual RGB image data

  return textureId; // Return the ID of the texture
}
```

Vertex Shader

```
#version 150

in vec3 vert;
in vec2 vertTexCoord;
out vec2 fragTexCoord;

void main()
{
  // Pass the tex coord straight through to the fragment shader
  fragTexCoord = vertTexCoord;

  gl_Position = vec4(vert, 1);
}
```

Fragment Shader

```
#version 150

uniform sampler2D tex; // this is the texture
in vec2 fragTexCoord;  // these are the texture coordinates
out vec4 finalColor;   // this is the output color of the pixel

void main()
{
  finalColor = texture(tex, fragTexCoord);
}
```

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Texture Coordinates

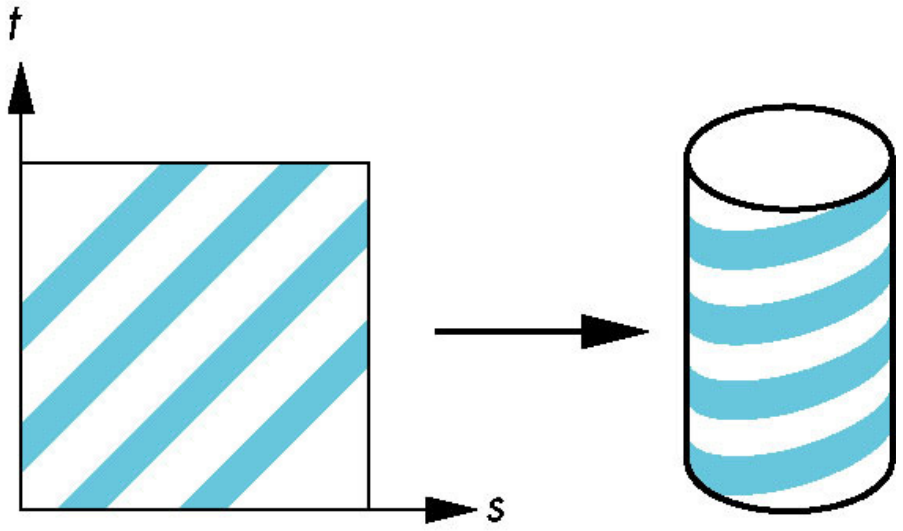
What if texture extends across multiple polygons?

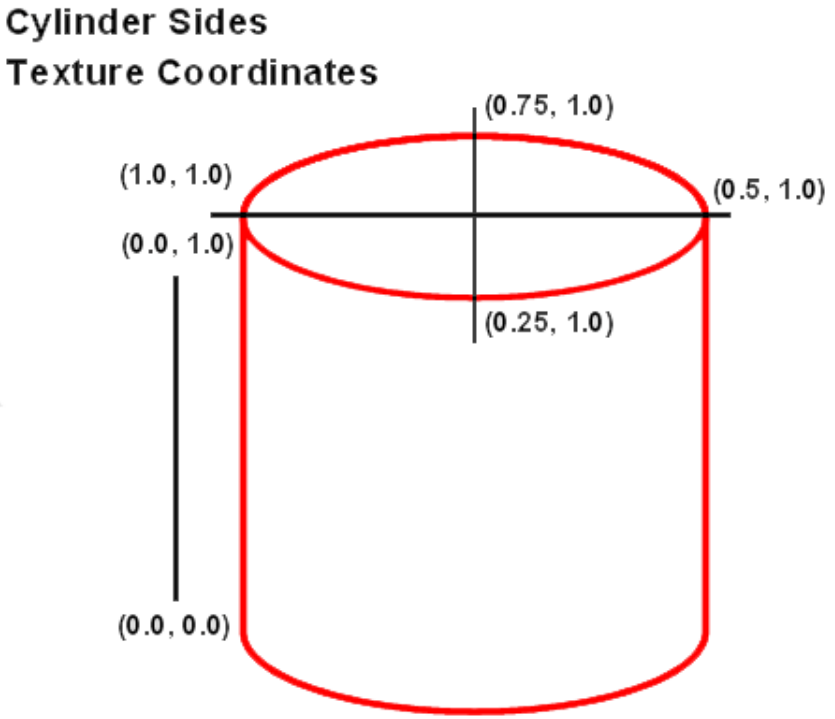
→ Surface parameterization

- Mapping between 3D positions on surface and 2D texture coordinates
  - Defined by texture coordinates of triangle vertices
- Options for mapping:
  - Cylindrical
  - Spherical
  - Orthographic
  - Parametric
  - Skin

Cylindrical Mapping

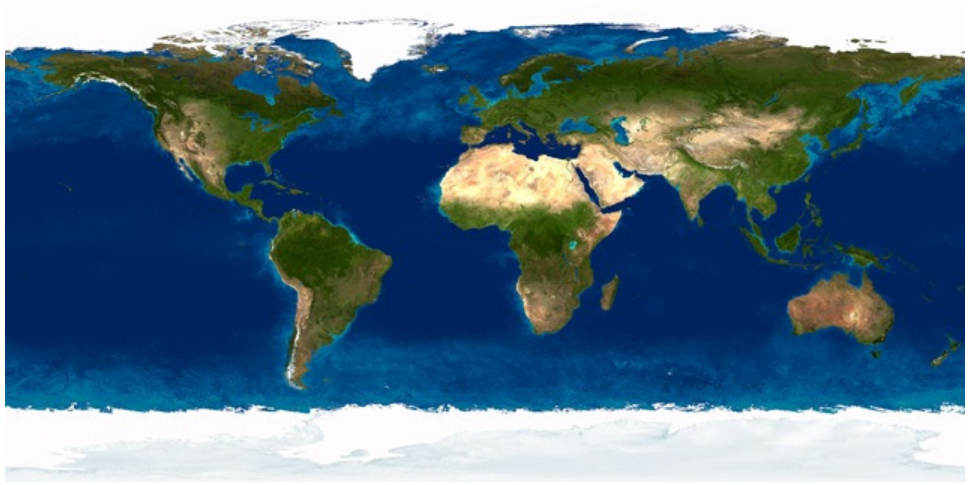
- Similar to spherical mapping, but with cylindrical coordinates





Spherical Mapping

- Use spherical coordinates
- "Shrink-wrap" sphere to object



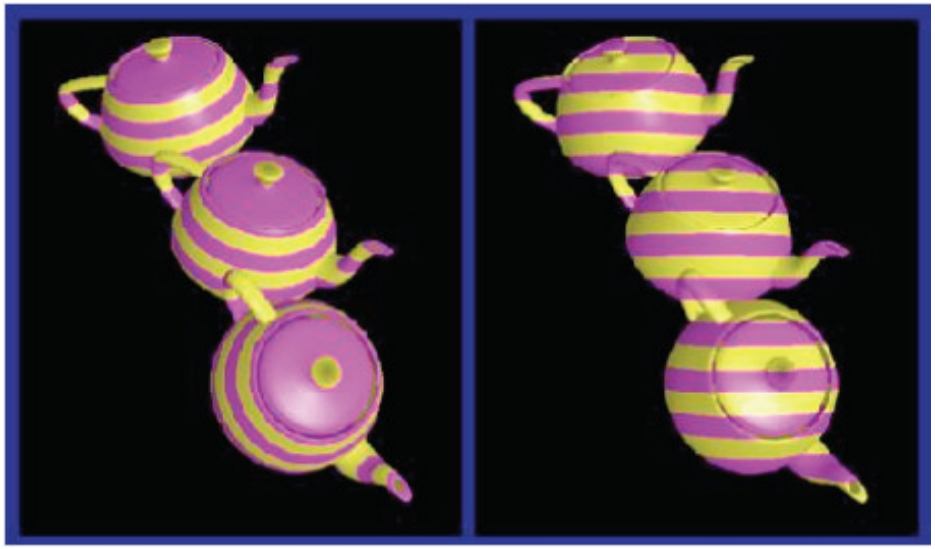
Texture map

Mapping result

Orthographic Mapping

- Use linear transformation of object's xyz coordinates
- Example:

$$\begin{bmatrix} s \\ t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}$$



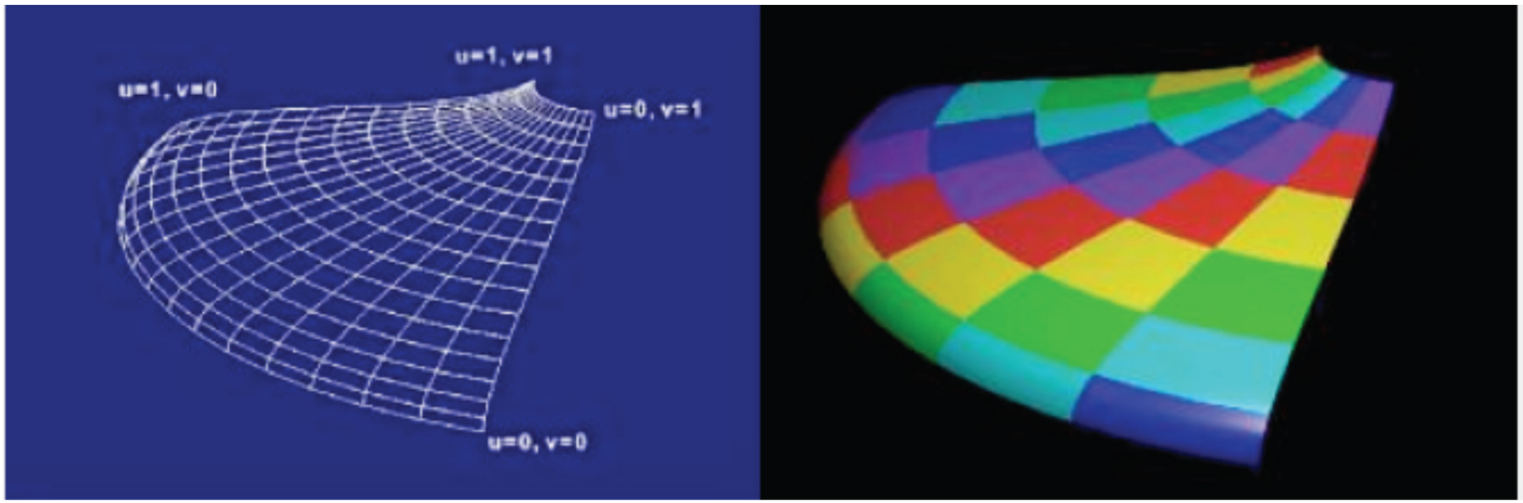
xyz in object space *xyz in camera space*

Parametric Mapping

- Surface given by parametric functions

$$x = f(u,v) \quad y = f(u,v) \quad z = f(u,v)$$

- Very common in CAD
- Clamp (u,v) parameters to [0..1] and use as texture coordinates (s,t)



Skin Mapping